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Evaluation of Donnan Dialysis for Treatment of Nickel Plating Rinsewater

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EVALUATION OF DONNAN DIALYSIS FOR TREATMENT OF NICKEL PLATING RINSEWATER

by

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16. ABSTRACT

A program to demonstrate the feasibility of metal salt recovery and pollution control by ion selective diffusion, also known as Donnan dialysis was conducted on a Watts type nickel plating line. The objective of the program was to demonstrate the tubular membrane configuration and to determine the suitable operating conditions for this equipment.

Several modules, consisting of tubular cation exchange membrane material mounted within a shell, were used to remove nickel ion from plating rinsewater with accompanying replacement of the nickel by hydrogen ion. Recovery rates were determined at various operating conditions.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

This report describes the technical feasibility of using Donnan dialysis for treatment/recovery of nickel plating rinsewaters under actual plant conditions. Donnan dialysis differs from the other membrane separation processes in that the driving force is a result of concentration differences across the membrane as opposed to pressure or electrical potential differentials. This report will be useful to EPA and the private sector concerned with the treatment of wastewaters from various metal finishing, non-ferrous metal, steel, inorganic and other industries.

For further information, please contact the Alternative Technologies Division of the Hazardous Waste Engineering Research Laboratory.

David G. Stephan, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

A program to demonstrate the feasibility of metal salt recovery and pollution control by ion selective diffusion, also known as Donnan dialysis was conducted on a Watts type nickel plating line. The objective of the program was to demonstrate the Donnan dialysis system for recovery of nickel utilizing the tubular membrane configuration and to determine the suitable operating conditions for this equipment.

Several modules, consisting of tubular cation exchange membrane material mounted within a shell, were used to remove nickel ion from plating rinsewater with accompanying replacement of the nickel by hydrogen ion. Recovery rates were determined at various operating conditions in order to specify the equipment for commercial use with emphasis on practicality, economics, reliability, and limitations.

This report was submitted in fulfillment of Grant No. R-804655 by the Seaboard Metal Finishing Company, Inc. The report covers the period March 1978 to June 1979, and work was completed as of June 1981.

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SECTION 1

INTRODUCTION

Current concern over the presence of metallic ions in the watershed has caused the government to restrict and regulate wastewater discharge practices prompting industry to investigate certain recovery processes where the technology is sufficiently advanced to offer payback and compete with conventional disposal methods. Three of these processes depend on membranes for effecting separation; reverse osmosis, electrodialysis, and Donnan dialysis also known as ion diffusion separation. Driving force for the first two processes are respectively pressure and electrical potential. Driving force for Donnan dialysis, however, is the membrane potential related to concentration differences across the membrane.

Utilizing the permselective properties of ion-exchange membranes one can cause an equilibrium to become established between two solutions of electrolytes separated by the membrane. In the case of the cation exchange membrane used in this project, the anionic species in the solutions are prevented from diffusing while the mobile cationic species will distribute themselves until at equilibrium:

$$\left(C_{il}/C_{ir}\right)^{1/z} = \left(C_{jl}/C_{jr}\right)^{1/z} = \left(C_{kl}/C_{kr}\right)^{1/z} = k$$

Where i, j, and k are cationic species, z is their respective valence, C is concentration, and l and r refer to left and right sides of the membrane. The driving force for the cation transfer from one side to the other is, therefore, the magnitude of the systems displacement from equilibrium, and this driving force can be affected by varying the solution concentrations. The extent that equilibrium conditions will be achieved depends on electrolyte concentration, membrane properties, and operating conditions.

This program concerned the study of Donnan dialysis as a means of concentrating nickel ions from plating rinsewaters using hydrogen ion from dilute sulfuric acid as the other mobile cationic species.

SECTION 2

CONCLUSIONS

Donnan dialysis is an effective process for recovery of nickel ion from electroplating rinse water.

By recirculating rinse water from a Watts-type nickel plating line through a Donnan dialysis unit fitted with permselective cation exchange membranes and utilizing a strip solution of 1 Normal sulfuric acid as the source for other cation species, it was possible to remove over 6.6 grams of nickel per square meter of membrane per hour (0.0044 $lb/ft^2/hr$) from the rinse water thus prolonging the life of the rinse solution. This process generates a concentrated solution with nickel ion levels in excess of 30 grams per liter (0.25 lb/gal) and is useful to replace the nickel removed from the electroplating bath and to help control the plating bath pH.

Economic advantages lie in the savings of raw material costs, the reduction of conventional disposal costs, reasonable capital investment costs and lower operating costs than the electrical and high pressure driven dialyses processes.

SECTION 3

RECOMMENDATIONS

Variables affecting the rate of recovery of nickel ion from wastewater have been thoroughly examined both in controlled laboratory tests and in actual on-site operations of the Donnan dialysis unit. Separation in this unit was accomplished using modular hollow tube cation exchange resin of the perfluoro sulfonic acid type. This process also can be carried out using the conventional plate or frame configuration, such as is typical of the electrodialysis multicell.

Plate and frame multicells while larger than tubular modules have been shown to enjoy long life expectancy in nickel recovery operations. Such stacks should be tested in series and parallel combinations under operating conditions similar to those described herein. Techniques for nickel recovery by this method should then be adapted for recovery of other ionic species.

SECTION 4

BACKGROUND

Reconstruction of Existing Equipment

A prototype Donnan dialysis unit was installed at Seaboard Metal Finishing Company in West Haven, CT. on Watts-type nickel electroplating line. The originally installed system failed to achieve the anticipated performance according to its design. Thus, Donnan dialysis unit was shipped to the Chemical Recovery Systems laboratories in Fall River, Massachusetts, for inspection, repair, and redesign. Three of the dialysis modules were examined at Chemical Recovery Systems and one module was evaluated by Du Pont in Wilmington. Three units were checked for flow and leakage. In all cases, maximum flow observed was 4.17 l/m (1.1 gal/m) at 68.9 kN/m^2* (10 psig) which is significantly below the 18.9 l/m (5 g/m) at 20.7 kN/m^2 (3 psig) anticipated in the original design of the system. No clogging was evident judging by visual inspection and reverse flow measurements followed by sulfuric acid back-flushing. One module was dissambled and inspected. Tube count was 386 and based on 0.064 cm (0.025 in. I.D. or 0.089 cm (0.035 in. O.D.) and tube length of 157 cm (62 in.) surface area of membrane is either 1.21 or 1.67 m^2 (13 or 18 ft^2) of available membrane. Very little leakage was observed but a few pinhole leaks required considerable effort to seal. Failure was determined to be in the housing, not the membranes.

One module was used in a series of preliminary dialysis tests to determine operating characteristics and to prepare for later tests. Simulated nickel rinse solutions were dialyzed at flows between 0.063 and 3.78 l/m (0.017 and 1 g/m). Feed solution concentrations, flowing on the tube side of the membranes, were varied between 0.025 and 0.164 g/l (0.0014 lb/gal) of nickel. Feed flows were varied from 0.44 to 2.84 l/m (0.12 to 0.75 g/m). Strip solutions of 0.5 and 1 Normal sulfuric acid were flowed at rates from 37.8 to 378 l/m (10 to 100 gal/m) on the shell side of the membrane. Flux was found to increase both with increased feed flow and increased feed (rinse) concentration. Percent removal was in the 40 to 50% range for all operating conditions except extremely low feed flow rates where removal of 75 to 85% could be achieved. Strip concentrations of 0.5 and 1.0 Normal sulfuric acid gave identical results as long as the acid concentration was maintained. Also the flow direction, countercurrent or concurrent, had no effect on the removal rates. Table 1 lists typical data illustrating relationship between feed (rinse) flow rates and flux. Data in Table 2 similarly show the effect of increasing flux with increased feed concentration. And data in Table 3 show that flux is quite generally independent of strip flow rate in these ranges.

*gauge pressure

TABLE 1. EFFECT OF FEED FLOW RATE ON FLUX

Feed Flow (liters per hour)	Volume of Product Produced (liters)	Product Concentration (g/l Nickel)	Flux (grams per hour)	% Cut
56.8	56.8	0.013	0.74	52
113.8	113.7	0.013	1.48	52
170.5	170.5	0.012	2.05	48
189.5	189.5	0.012	2.27	48

Feed Concentration - 0.025 g/l Nickel
Strip Flow Rate - 189.5 liters per hour
Strip Solution - 1 Normal sulfuric acid

TABLE 2. EFFECT OF FEED CONCENTRATION ON FLUX

Feed Flow Rates (liters per hour)	Flux at Various Feed Concentrations (grams of Nickel per liter)				
	0.025 g/l	0.029 g/l	0.065 g/l	0.098 g/l	0.106 g/l
56.8	0.74	0.93	1.71	2.90	3.01
113.7	1.48	1.82	3.75	6.14	6.37
170.5	2.05	2.56	5.63	8.19	8.19
189.5	2.27	2.81	----	----	----

Strip Flow Rate - 189.5 liters per hour
Strip Solution - 1 Normal sulfuric acid

TABLE 3. EFFECT OF STRIP FLOW RATE ON FLUX

	FLUX AT VARIOUS FEED AND STRIP FLOW RATES			
FEED CONCENTRATION	0.098 g/l		0.106 g/l	
FEED FLOW RATE	56.8 l/hr	113.7 l/hr	56.8 l/hr	113.7 l/hr
Strip Flow Rate - (liters/hr)				
37.9	2.73	----	3.01	----
94.8	2.90	----	3.07	----
189.5	2.90	6.14	3.01	6.37
379.0	2.90	5.80	3.18	6.37

Strip Concentration - 1 Normal Sulfuric Acid

Since this project was a continuation of the original demonstration program at Seaboard Metal Finishing Company, it was decided to replace all the membrane modules with newly fabricated perfluorinated ion exchange membrane tubular modules. Reconstruction of the unit was carried out to accommodate these new modules as well as to provide greater flexibility in operating conditions (see Figures 1-4). Hydraulic testing with water was performed to check for leaks, observe pressure and flow characteristics and indicate design changes which would provide ease of operation and ability to interchange the Nafion® (E.I. Du Pont De Nemours Company) mass exchangers. A total of six Nafion® exchangers supplied by du Pont were installed in two groupings designated front (F-1, F-2, F-3, and F-4) and rear (R-1 and R-2). Piping and valving allowed for choice of either parallel or series feed flow in the front exchangers each of which was fitted with a pressure gauge, sampling port, cartridge filter and flowmeter. The rear exchangers were piped for series flow only and while R-1 had a pressure gauge, sampling port, cartridge filter and flowmeter, R-2 was fitted with a pressure gauge and sampling port only. All of these fittings were located downstream of the system to allow for product sampling. The accompanying feed side flow schematic (Figure 3) illustrates the piping and valving described above. Note that this schematic shows only the feed (rinse) flow which is always downflow and always on the tube (inner) side of the Nafion® membrane. The strip solution (not shown) is always counter-current and upflow and always in parallel flow for the front four exchanges and in series for the rear two. Normally all exchangers operate with the same strip solution although a separate pump has been installed to allow for independent stripping solution to be run, if desired, for the two rear exchangers. Piping is such that the parallel strip flow is evenly distributed among the front four exchangers. Strip solution is contained in a 113.6 l (30 gal) tank and recirculated. The feed pump and the two strip pumps are magnetic drive centrifugal pumps designated for mild chemical solutions.

Installation On Site

The refitted dialysis unit was installed at Seaboard to treat the first of three counterflow rinses which follow the plating tanks and a spray rinse on a Watts-type nickel electroplating line. Rinse water from a second nickel line was also discharged through the recirculating counterflow tank giving a total discharge volume of approximately 1136 l/hr (300 gal/hr). The unit was located about 9.1 m (30 ft) from the counterflow rinse tank which was fitted with 3.8 cm (1.5 in.) and 3.2 cm (1.25 in.) PVC pipe for suction and return, respectively. Average nickel (metal) concentration of the rinse solution was found to be 0.452 g/l (0.004 lb/gal) based on 82 samples taken over a three month period preceding installation. Concentration range was 0.13 to 1.04 g/l (0.001 to 0.009 lb/gal). Initial testing of the dialysis unit using the actual rinse solution averaged 0.694 g/l (0.006 lb/gal) of nickel, and strip solution concentration increased to 4.85 g/l (0.040 lb/gal). Predominant mode of operation was parallel flow through the four front exchangers. As a result of this brief test, several equipment modifications were made solely for the purposes of improving the operations. Valving to isolate individual modules was installed, sampling ports were installed, piping was shortened to allow for ease of drainage and to improve hydraulics, and strainers and clean-out ports were added.

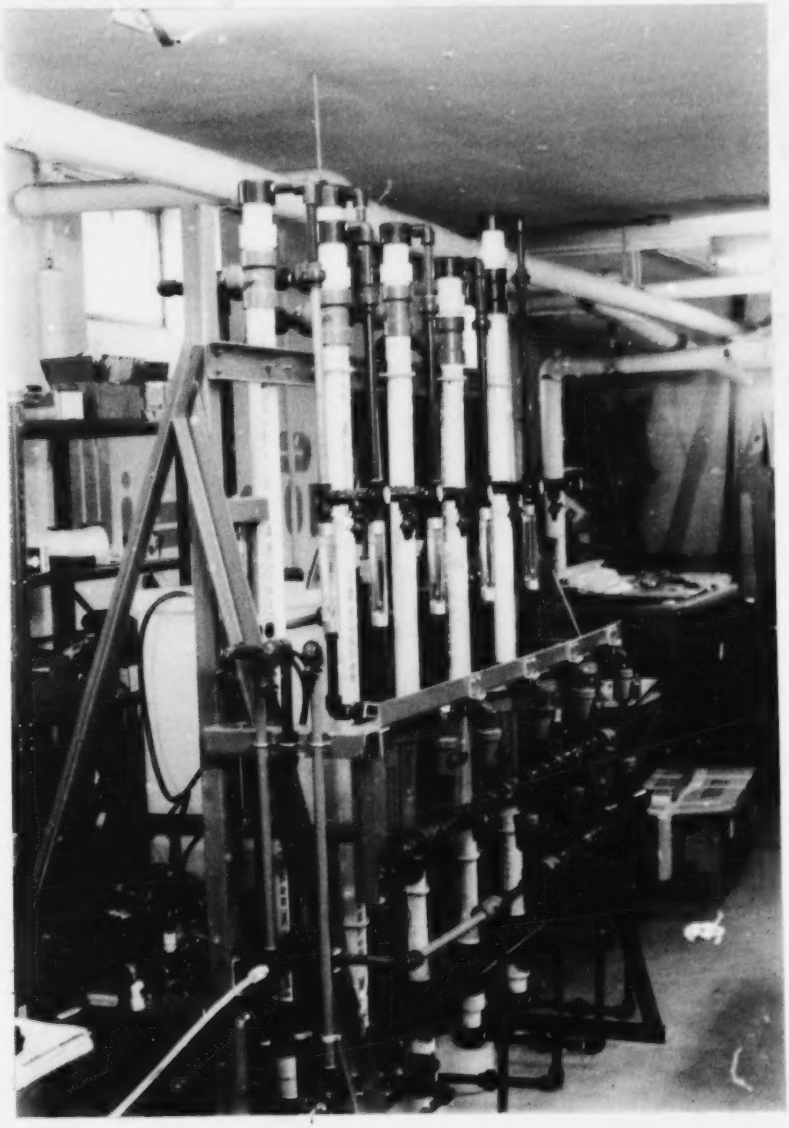


Figure 1. Tubular Donnan Dialysis System.

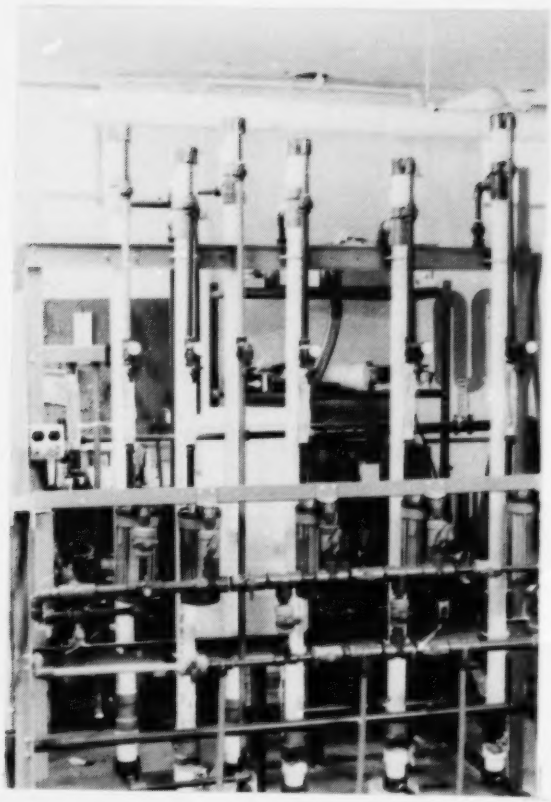
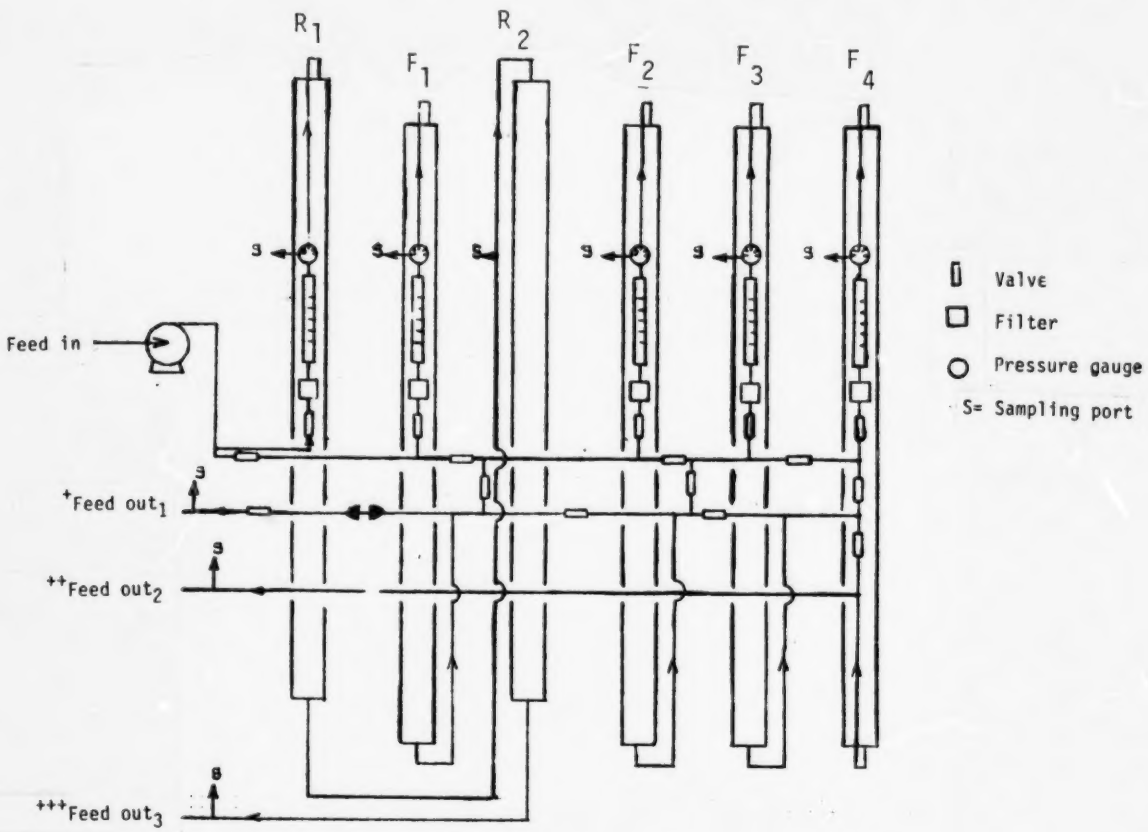


Figure 2. Donnan Dialysis System on-site.



+ Parallel flow through F_1-F_4
++ Series flow through F_1-F_4
+++ Series flow through R_1-R_2

Figure 3. Feed side flow schematic.

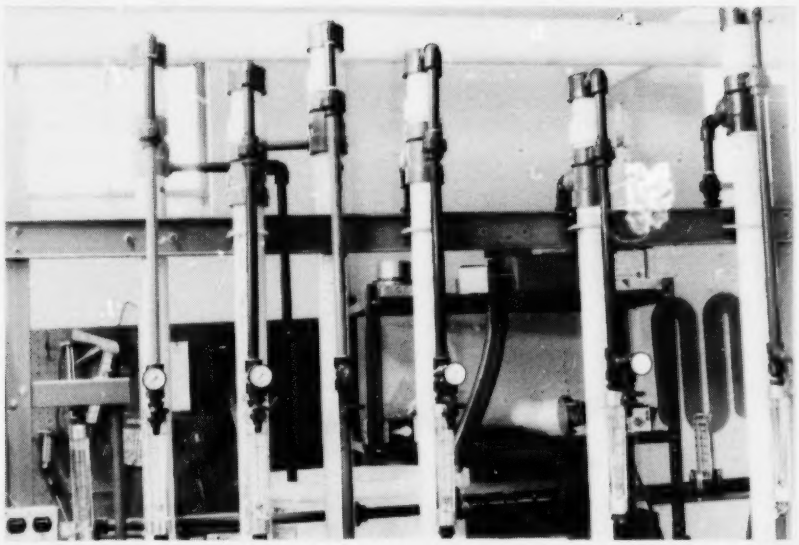


Figure 4. Donnan Dialysis System - sampling ports, flow meters and pressure gauges.

Start-up and Operation

The first series was designed to determine the performance of the exchangers and to decide on the most convenient method for handling the strip and rinse solutions. As installed, the rinse solution to be treated was recirculated through the Donnan unit and returned to the rinse tank. Normal plating and rinsing operations continued without interruption. The strip solution was recirculated from a 113.5 l (30 gal) tank, and flow was always parallel through the exchangers and counterflow to the rinse solution. A fresh strip solution consisted of fresh water plus sufficient sulfuric acid to give an acid concentration greater than 1 Normal. Volume of this solution increased during operation because of osmotic flow of water into the solution at a rate of approximately 0.95 l/hr (0.25 gal/hr) per exchanger. This volume increase must be considered in calculating nickel concentration, nickel transfer rates and flux. New strip solution was not required for each day's operation. Instead, before starting operation the strip from the previous day's operation was reduced to 75.7 l (20 gal), and acid was added to regenerate the original concentration. Excess strip solution was used to replace nickel in the plating tanks and to help control pH. Evaporation from these tanks was adequate to allow addition of the concentrated nickel product. This was accomplished either manually or mechanically using one of the pumps on the unit properly fitted with distribution tubing.

Initial on-site operations with actual rinse water conditions were undertaken with parallel feed flow to the four front exchangers at 681 l/hr (180 gal/hr). Duration of the run was 3.25 hr in which time the feed concentration was between 0.75 and 1.19 g/l (0.006 and 0.010 lb/gal). Feed pH ranged from 1.4 to 2.2. Strip solution concentration increased from 3.0 to 7.4 g/l as nickel (0.025 to 0.062 lb/gal) while sulfuric acid concentration dropped from 1.5 N to 1.4 N. Based on actual analyses, nickel concentration in the strip increased by 1.6 g/l (0.013 lb/gal) in the first hour and by 2.8 g/l (0.023 lb/gal) in the next 75 minutes. Considering the increased nickel content of the strip and correcting for the osmotic volume increase of the solution, flux values of 19.4 and 29.0 g/hr/m^2 (0.004 and 0.006 lb/hr/ft^2) were calculated.

Continuing in this mode for two more days, then running at 1136 l/hr. (300 gal/hr) for five days and at 454 l/hr (120 gal/hr) for three additional days, we collected separation data summarized in Table 4.

TABLE 4. INITIAL ON-SITE RESULTS

Feed Flow Rate (l/hr)	Average Feed Concentration g/l	Average Nickel Transport g/hr	Average Flux g/hr/m^2
681	0.72	163	21.5
1136	0.66	176	23.7
454	0.80	210	28.0

The data showed that both increases in feed concentration and feed flow rate caused an increase in the transport rate, here recorded as Flux, which at 1136 l/hr (300 gal/hr) was greater than at 681 l/hr (180 gal/hr) in spite of a slightly lower feed concentration. At a flow of 454 l/hr (120 gal/hr) the major influence is the higher concentration which produces a higher flux in spite of the lower flow rate. Results at 681 to 908 l/hr (180 to 240 gal/hr) and 0.86 g/l (0.007 gal/hr) nickel feed were consistently giving a flux of 29.0 g/hr/m^2 (0.006 lb/hr/ft^2). Similarly, at a flow of 454 l/hr (130 gal/hr) and feed concentration of 0.38 g/l (0.003 lb/gal), a flux of 10.8/g/hr/m^2 (0.002 lb/hr/ft^2) was realized.

Strip solution concentration was maintained at about 1 Normal sulfuric acid gradually decreasing during each day. Acidity was determined by titration of first and last samples daily. Variations did not seem to effect transport rate as long as the concentration remained at 1 Normal or above. Feed concentration, to be sure, varies through the course of the day according to the activity of the plating line. In addition, rinse water from a second line discharges through the rinse tank being treated, giving a total flow through the tank of 1136 l/hr (300 gal/hr).

During the series of tests described above, the strip concentration was allowed to increase to over 30 g/l (0.25 lb/gal) with no apparent deterioration in flux. This is significant since the plating bath concentration was about 85 g/l (0.71 lb/gal) as nickel and it is the objective of this recovery technique to produce a concentrate which can be added to the plating bath without excessive dilution effects. Further, maximum utilization of acid is realized here and solution bulk is kept at a minimum, facilitating ease of transferring or other handling. Temperature has not been controlled during these tests but has been observed to be in the range 15.6-18.3° C (60-65° F). Higher temperatures are believed to produce some improvement in flux, but in the 0.5 to 1.0 g/l (0.004 to 0.008 lb/gal) nickel rinse concentration range, flux values of 21.5 to 32.3 g/hr/m^2 (0.004 to 0.007 lb/hr/ft^2) may be about the maximum attainable with the exchangers now in use.

It was decided to explore rates for the individual exchangers using a fresh strip solution for each test. The results were as follows:

TABLE 5. EFFECT OF FRESH STRIP SOLUTION ON FLUX

Exchanger	Average Rinse Concentration (g/l)	Average Nickel Transport (g/hr)	Average Flux (g/hr/m^2)
F-1	0.41	34	18.3
F-2	0.86	45	24.7
F-3	1.05	69	37.7
F-4	1.09	88	47.3

Taking into account the increasing rinse concentration, exchangers F-1, F-2, and F-3 exhibit similar performance and transport is consistent with earlier results of parallel flow orientation. Exchanger F-4, however, appears to be significantly more efficient although at this time no explanation can be offered.

The four front exchangers were next run in series. These runs showed generally lower nickel transport, but this should be expected since initial rinse concentration was, of course, gradually reduced on passing through each successive exchanger, and it has been shown that flux can be expected to be reduced at reduced feed (rinse) concentration. Values of 14.0 to 17.2 g/hr/m^2 (0.003 to 0.004 lb/hr/ft^2) were realized in this series flow experiment.

The front four exchangers were next returned to parallel operation to confirm the effect of flow rate on flux. Runs were conducted at flow rates ranging from 454 to 908 l/hr (120 to 240 gal/hr). Feed concentration varied only from 0.57 to 0.89 g/l (0.005 to 0.007 lb/gal). Temperature was recorded but not controlled. The results are as follows:

TABLE 6. EFFECTS OF PARALLEL OPERATION ON FLUX

Date	Temperature °C	Feed Concentration (g/l)	Flow Rate (l/hr)	Nickel Transport (g/hr)	Flux (g/hr/m^2)
1/9	14.4	0.71	908	193	25.8
1/10	12.2	0.71	908	179	24.7
1/11	12.2	0.57	908	158	21.5
1/25	14.4	0.58	454	143	19.4
1/26	11.7	0.70	454	140	18.3
1/29	12.2	0.89	454	148	20.4
1/30	12.2	0.86	454	157	21.5
1/31	12.2	0.84	454	176	23.7

Higher flux is attainable at higher feed concentrations and higher feed flow rates. Temperature variations as observed here were probably not significant in affecting transport.

Evaluation of the individual exchangers was continued in the next series of runs. The results are listed in Tables 7 and 8.

TABLE 7. SEPARATION FACTORS FOR INDIVIDUAL EXCHANGERS

Exchanger	Feed Concentration (g/l)	Nickel Transport (g/hr)	Flux ($g/hr/m^2$)
F-1	0.80	39	21.5
F-1	0.62	48	25.8
F-2	0.51	40	21.5
F-2	0.68	56	30.1
F-2	0.82	60	32.3
F-3	0.89	48	25.8
F-4	0.89	58	31.2

Again F-4 exchanger was found to be more efficient than the other three exchangers. Subsequent investigation showed this tube is of an improved design which would indicate the possibility of upgrading the total performance of this type of equipment in the future.

The next set of runs designed to test the effects of increased acidity in the strip solution were conducted as controls with strip acidity at 1.1 to 1.8 Normal and all four front exchangers operating in parallel. Flux for these control runs was 22.3 $g/hr/m^2$ (0.005 $lb/hr/ft^2$) at average feed concentration of 0.72 g/l (0.006 lb/gal) and flow at 681 l/hr (180 gal/hr). Doubling the acid concentration of the strip from 1.9 to 3.6 Normal and operating as above with all four exchangers in parallel, feed concentration averaging 0.73 g/l (0.006 lb/gal) and flow at 908 l/hr (240 gal/hr) gave flux values from 26.9 to 30.1 $g/hr/m^2$ (0.005 to 0.006 $lb/hr/ft^2$). These values are significantly higher and were checked out later in a new series. A repeat gave substantially the same result, flux of 28.0 $g/hr/m^2$ (0.006 $lb/hr/ft^2$).

The next runs were conducted with the front four exchangers piped in series flow. We found that at feed concentrations averaging 18% higher, flux values averaged 22.6 $g/hr/m^2$ (0.005 $lb/hr/ft^2$) for the runs made with lower feed concentration, in spite of reduced flow rates of 681 versus 749 l/hr (150 versus 198 gal/hr) for the earlier tests. Strip concentrations and operating temperature were nearly the same in both sets of runs.

The results are listed below:

TABLE 8. EFFECTS OF FEED CONCENTRATION AND REDUCED FLOW RATES ON FLUX

Feed Concentration	Flow Rate (l/hr)	Flux ($g/hr/m^2$)
0.73	749	14.0
0.81	772	17.2
1.07	749	17.2
0.94	568	22.6
1.31	568	17.2
1.09	568	24.7
0.94	568	20.4
0.91	568	24.7
0.90	568	21.5
0.83	568	23.7
1.18	568	25.8
1.20	568	25.8

Until this time all dialysis tests have involved only the four front exchangers in either single, series operation or parallel operation. We next scheduled tests to evaluate the rear exchangers R-1 and R-2 which were hard piped for series operation only. At relatively high feed concentrations these modules gave only average yield of nickel ion suggesting again that series operation is less efficient because of the decreasing nickel concentration in the feed as it passes from one exchanger to the next.

TABLE 9. EFFECT OF SERIES OPERATION ON FLUX (2 MODULES)

Date	Feed Concentration (g/l)	Nickel Transport (g/hr)	Flux ($g/hr/m^2$)
3/7	0.86	108	29.0
3/9	1.24	109	29.0
3/12	1.74	101	26.9

If four exchangers had been employed in these runs we would, of course, have expected to see much lower flux values because of this effect of decreasing feed concentration as the flow is from one exchanger to another.

To confirm this, we ran a set of five runs using only the four front exchangers, this time piped for series flow. In spite of relatively high feed concentration, we once more realized unacceptably low nickel transport averages.

TABLE 10. EFFECT OF SERIES OPERATION ON FLUX (4 MODULES)

Date	Feed Concentration (g/l)	Nickel Transport (g/hr)	Flux ($g/hr/m^2$)
3/26	1.16	159	21.5
3/27	0.77	118	16.1
3/29	0.92	114	15.1
3/30	1.09	128	17.2
4/3	0.73	152	20.4

For the next set of runs, feed and strip streams have been reversed to investigate the effects of operating the mass exchangers with the rinse on the shell side and the strip on the tube side of the membranes. This is the reverse of our current operating procedure. Consequently we repiped the existing unit to conform to the newly recommended flow arrangement in an effort to improve the nickel transport values obtained heretofore. A set of five runs using only front exchangers in parallel was undertaken to compare with earlier results obtained with our usual procedure. Rinse

(feed) concentrations remained relatively high and flow rate was varied from 681 to 1136 l/hr (180 to 300 gal/hr). The data shows no significant improvement in nickel transport:

TABLE 11. EFFECT OF TUBE SIDE STRIPPING ON FLUX

Feed Concentration (g/l)	Flow Rate (l/hr)	Nickel Transport (g/hr)	Flux ($g/hr/m^2$)
0.88	681	188	25.8
0.94	681	155	20.4
0.28	1136	124	17.2
0.83	681	180	23.7
0.75	795	158	21.5

To maximize nickel recovery, we next scheduled a group of runs using all six exchangers, the four front modules piped in parallel and the rear two modules piped in series. Shell side feed and the tube side strip remain as above. Feed concentrations were not as high as in recent runs, but nickel transport again was found to increase with increasing feed concentration and higher flowrates. Flux, of course, was affected adversely by the series arrangement of the rear exchangers.

TABLE 12. SEPARATION FACTORS FOR G MODULE OPERATION

Feed Concentration (g/l)	Flow Rate (l/hr)	Nickel Transport (g/hr)	Flux ($g/hr/m^2$)
0.73	681	212	19.4
0.81	681	217	19.4
0.39	1249	190	17.2
0.52	1136	211	19.4
0.55	681	161	14.0

At several times during the test program grab samples were taken before and after each mass exchanger and analyzed for nickel content in order to determine nickel removal rate for each pass through a given module. Percent reduction in nickel concentration was calculated from the nickel for feed entering and exiting from each tube. Sampling techniques and mixing variables cause a great deal of uncertainty regarding the reliability of these data. However, we feel that the percent cut or percent nickel removal lies in the range 15% to 25%. Some data are given below:

TABLE 13. PERCENT NICKEL CONCENTRATION REDUCTION

Nickel Concentration (In) (g/l)	Nickel Concentration (Out) (g/l)	% Cut
0.84	0.71	15
0.75	0.57	24
0.57	0.41	28
1.09	0.93	15
0.93	0.82	12
0.82	0.56	32
0.56	0.51	9
0.90	0.84	7
0.84	0.76	10
0.76	0.69	9
0.69	0.47	32
1.07	0.98	18
0.98	0.81	17
0.81	0.71	12
0.71	0.56	21
1.47	1.26	14
1.26	1.07	15
1.07	0.93	13

Continued

TABLE 13. Continued

Nickel Concentration (In) (g/l)	Nickel Concentration (Out) (g/l)	% Cut
0.93	0.74	20
1.62	1.47	9
1.47	1.25	15
1.25	1.09	13
1.09	1.98	10
0.66	0.56	15
0.53	0.47	11
1.22	1.04	15
0.62	0.38	39
0.58	0.43	26
1.17	0.93	21
1.01	0.85	16
1.04	0.91	13
0.73	0.58	21
0.74	0.50	32
0.99	0.74	25
0.90	0.72	20
0.85	0.75	12
0.76	0.68	11
1.37	1.18	14
0.98	0.74	25
1.75	1.04	40
0.57	0.41	28
0.66	0.45	33

Continued

TABLE 13. Continued

Nickel Concentration (In) (g/l)	Nickel Concentration (Out) (g/l)	% Cut
1.18	0.77	35
0.82	0.76	7
0.68	0.64	6
1.05	0.88	16
0.82	0.72	12
0.59	0.48	19

Temperature was recorded throughout the entire program, even through it could not be controlled. Generally ambient temperature readings were less than 16°C (68.8°F) until May when temperatures above 21.1°C (70°F) were noted. Fluctuations in this range were not deemed to have any significant effect on the dialysis rate, although higher temperatures, would likely lead to improved flux and should be investigated in a future program.

In all, 83 runs were undertaken. Seventy-one were completed, the results of which are reported here, while twelve were interrupted at some point because of breakdown, failure or other difficulty. Of the 71 reported here, the modes of operation were as follows:

Strip solution on the shell side
and front 4 exchangers in parallel
front 4 exchangers in series
investigation of single exchanger
rear exchangers only

Strip solution on tube side
and front 4 exchangers in parallel
front 4 exchangers in parallel with rear exchangers in series

No less than three runs were performed to establish average flux values. All data used in this report are listed in Table 20 in the appendix. Average daily feed concentrations are reported. Strip concentrations were determined by analysis of samples taken at the indicated time of day. Lapsed time is expressed as hour. The corrected strip volume takes into account the osmotic water transfer into the strip solution at a rate of approximately 0.95 l/hr (0.25 g/hr) per exchanger.

SECTION 5

RESULTS AND DISCUSSION

To specify optimum dialyzing conditions, it is necessary to evaluate all the operating conditions with reference to nickel transport thereby obtained. The question of whether the strip solution should be flowed on the shell side or the tube side of the membrane is likely related to the available membrane area. In fact, the shell side strip operations gave consistently higher nickel flux values as shown in Tables 14 and 15. Membrane area available on the shell side indeed is about 40% greater than on the tube side.

Investigation of parallel versus series flow through the membrane modules showed equally significant difference in performance. In all cases parallel operation gave at least 15% higher nickel (see Tables 17 and 18). Combined parallel-series operation gave lower flux values than would be expected and suggests that series operation should probably be restricted to polishing applications while parallel operation is particularly indicated for higher recovery rate systems.

All these data clearly show that the most effective operations were those runs in which the exchangers were piped in parallel configuration with a feed concentration of 0.5 g/l (0.004 lb/gal) or greater and with feed flow rates equal to or greater than 795 l/hr (210 gal/hr). With the mass exchangers used in these tests, flux was significantly greater when feed was circulated through the tubes and strip was flowed outside the membrane on the shell side.

Nickel transport values exceeding 200 grams per hour (0.44 lb/hr) were readily achieved by running all six mass exchangers and could be increased by piping the rear exchangers for parallel operation, the preferred mode. In several cases the strip solution concentration as nickel was allowed to increase to 30 g/l (0.25 lb/gal) with no apparent decline in flux. These findings plus our observation that temperature in the ranges recorded and feed solution pH did not significantly affect the dialysis results, lead us to recommend parallel operation of the six mass exchangers with strip solution on the shell side of the membrane, flow rate in excess of 795 l/hr (210 gal/hr), programming of the dialysis unit to function only when rinse approaches allowable upper limit nickel concentration, and recirculating of the strip solution to permit nickel concentrations to exceed 30 g/l (0.25 lb/gal).

Applications certainly exist for Donnan dialysis treatment of plating

rinsewaters utilizing either tubular membrane modules or plate and frame multicell stacks. Disposition of the sometimes unwanted dilute acid by-product would have to be considered on a site-by-site basis. Donnan dialysis should also be considered as a treatment complementing other technologies as part of the overall recovery and pollution control facility.

TABLE 14. SEPARATION RATES WITH STRIP ON SHELL SIDE

CONCENTRATION OF NICKEL IN FEED (g/l)	FLUX ($g/hr/m^2$)			
	<681 l/hr	681-795 l/hr	>795 l/hr	Average At All Flow Rates
0.28-0.50	10.8	----	23.7	20.4
0.51-0.80	21.5	22.6	23.7	22.6
0.81-1.00	21.5	25.8	26.9	23.7
1.01-1.74	20.4	17.2	37.7	26.9
Average At All Concentrations	21.5	22.6	26.9	23.2

TABLE 15. SEPARATION RATES WITH STRIP ON TUBE SIDE

CONCENTRATION OF NICKEL IN FEED (g/l)	FLUX ($g/hr/m^2$)			
	<681 l/hr	681-795 l/hr	>795 l/hr	Average At All Flow Rates
0.28-0.50	----	----	17.2	17.2
0.51-0.80	20.4	18.3	19.4	18.3
0.81-1.00	----	22.6	----	22.6
1.01-1.74	----	----	----	----
Average At All Concentrations	20.4	20.4	18.3	20.0

TABLE 16. SEPARATION RATES ALL RUNS

CONCENTRATION OF NICKEL IN FEED (g/l)	FLUX ($g/hr/m^2$)			
	<681 l/hr	681-795 l/hr	>795 l/hr	Average At All Flow Rates
0.28-0.50	10.8	----	21.5	19.4
0.51-0.80	21.5	22.6	22.6	22.6
0.81-1.00	22.6	23.7	26.9	23.7
1.01-1.74	20.4	17.2	28.0	24.7
Average At All Concentrations	21.5	23.7	24.7	22.6

TABLE 17. SEPARATION RATES PARALLEL RUNS

CONCENTRATION OF NICKEL IN FEED (g/l)	FLUX ($g/hr/m^2$)			
	<681 l/hr	681-795 l/hr	>795 l/hr	Average At All Flow Rates
0.28-0.50	10.8	----	22.6	20.4
0.51-0.80	23.7	21.5	23.7	22.6
0.81-1.00	23.7	26.9	26.9	24.7
1.01-1.74	----	----	28.0	28.0
Average At All Concentrations	22.6	22.6	24.7	23.0

TABLE 18. SEPARATION RATES SERIES RUNS

CONCENTRATION OF NICKEL IN FEED (g/l)	FLUX ($g/hr/m^2$)			
	<681 l/hr	681-795 l/hr	>795 l/hr	Average At All Flow Rates
0.28-0.50	----	----	----	----
0.51-0.80	18.3	14.0	----	17.2
0.81-1.00	20.4	17.2	----	20.4
1.01-1.74	20.4	17.2	----	19.4
Average At All Concentrations	20.4	16.1	----	19.4

TABLE 19. SEPARATION RATES COMBINED PARALLEL-SERIES RUNS

CONCENTRATION OF NICKEL IN FEED (g/l)	FLUX ($g/hr/m^2$)			
	<681 l/hr	681-795 l/hr	>795 l/hr	Average At All Flow Rates
0.28-0.50	----	----	17.2	17.2
0.51-0.80	----	16.1	19.4	18.3
0.81-1.00	----	19.4	----	19.4
1.01-1.74	----	----	----	----
Average At All Concentrations	----	18.3	18.3	18.3

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Appendix

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Vol. STRIP(1)	Total Nickel In STRIP(g)	Ni (g/l)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
1:30	0.97	3.0	----	79.6	239	----	----		----	
2:30		4.6	1.00	83.4	384	1.6	145	3	145	1.8
3:45		7.4	1.25	88.1	652	2.8	268	3	214	2.7
7:30	0.53	6.8	----	88.1	599	----	----		----	
1:55		12.8	6.4	112.3	1438	6.0	839	3	131	1.6
3:55		14.9	2.0	119.9	1787	2.1	349	3	174	2.2
8:00	0.66	3.6	----	79.6	287	----	----		----	
10:30		8.2	2.50	89.0	730	4.6	443	3	177	2.2
12:00		10.4	1.50	94.8	985	2.2	255	3	170	2.1
3:50		13.6	3.83	109.3	1486	3.2	501	3	131	1.6
7:35	0.68	8.0	----	83.3	667	----	----		----	
3:45		20.0	8.20	114.3	2289	12.0	1622	3.4	198	2.5
8:00	0.95	1.3	----	80.0	104	----	----		----	
3:30		13.6	7.50	108.0	1469	12.3	1365	5	182	2.3
7:30	0.49	2.3	----	79.6	183	----	----		----	
12:50		9.4	5.33	99.7	938	7.1	755	5	142	1.8
1:40		10.8	.83	102.9	1112	1.4	174	5	210	2.6
2:20		11.3	.67	105.4	1192	0.5	80	5	119	1.5
4:05		13.9	1.75	112.0	1558	2.6	366	5	209	2.6
8:20	0.86	2.3	----	79.6	183	----	----		----	
10:10		6.8	1.83	86.6	588	4.5	405	3.5	221	2.8
4:00		16.5	5.83	108.6	1792	9.7	1204	3.5	207	2.6

(continued)

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Total Vol. STRIP(1)	Nickel In STRIP(g)	Ni (g/l)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
7:30	0.76	15.2	----	79.6	1209	----	----		----	
11:30		16.8	4.00	94.7	1592	1.6	383	5	96	1.2
2:30		19.4	3.00	106.0	2059	2.6	467	5	156	2.0
5:15		26.17	2.75	116.4	3050	6.8	991	5	360	4.5
6:00		26.46	0.75	119.2	3159	0.3	109	5	145	1.8
8:30	0.54	19.6	----	79.6	1560	----	----		----	
10:45		23.2	2.25	88.1	2044	3.6	484	5	215	2.7
1:30		22.6	2.75	98.5	2227	-0.6	183	5	67	0.8
4:30		23.5	3.00	109.8	2583	0.9	356	5	119	1.5
9:00	0.50	25.5	----	79.6	2030	----	----		----	
3:30		30.9	6.50	104.2	3221	5.4	1191	5	183	2.3
8:45	0.81	4.3	----	79.6	342	----	----		----	
2:00		14.6	5.25	99.4	1453	10.3	1111	2	212	2.7
3:45		17.9	1.75	106.0	1900	3.3	447	2	255	3.2
7:45	0.76	15.6	----	79.6	1242	----	----		----	
1:37		22.9	5.87	101.8	2332	7.3	1090	2	186	2.3
3:25		25.6	1.80	108.6	2782	2.7	450	2	250	3.1
8:00	0.38	22.3	----	79.6	1775	----	----		----	
10:20		21.6	2.33	88.4	1910	-0.7	135	2	58	0.7
4:30		22.5	6.13	111.6	2512	0.9	602	2	98	1.2
8:45	0.84	19.4	----	79.6	1544	----	----		----	
2:00		23.2	5.25	99.4	2308	3.8	764	2	146	1.8
4:00		25.6	2.00	107.0	2741	2.4	433	2	216	2.7

(Continued)

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Vol. STRIP(1)	Total Nickel In STRIP(g)	Ni (g/l)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
12:00	0.41	3.38	----	79.6	269	----	----		----	
2:30		4.56	2.50	82.0	374	1.18	105	5	42	2.1
4:15		5.0	1.75	83.7	419	0.44	45	5	26	1.3
10:20	0.86	1.45	----	79.6	115	----	----		----	
1:35		2.94	3.25	82.7	243	1.49	128	5	39	2.0
5:00		4.85	3.42	85.9	417	1.91	174	5	51	2.6
11:20	1.05	1.03	----	79.6	82	----	----		----	
1:30		2.50	2.17	81.7	204	1.47	122	5	56	2.8
3:30		4.41	2.00	83.6	368	1.91	164	5	82	4.1
12:00	1.09	1.18	----	79.6	94	----	----		----	
2:30		3.99	2.50	82.0	327	2.81	233	5	93	4.7
4:10		5.59	1.67	83.6	467	1.60	140	5	84	4.2
8:25	0.73	2.06	----	79.6	164	----	----		----	
2:30		8.38	6.08	102.6	860	6.32	696	3.3	115	1.4
4:15		9.41	1.75	109.2	1028	1.03	168	3.3	96	1.2
8:00	0.81	2.43	----	79.6	193	----	----		----	
12:00		6.17	4.00	94.7	585	3.74	392	3.4	98	1.2
4:20		11.32	4.33	111.1	1258	5.15	673	3.4	156	1.9
8:20	1.07	10.73	----	79.6	854	----	----		----	
1:45		15.29	5.58	100.7	1540	4.56	686	3.3	123	1.6
4:00		16.61	2.25	109.2	1815	1.32	275	3.3	122	1.6

(Continued)

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Total Vol. STRIP(1)	Nickel In STRIP(g)	Ni (g/1)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
10:00	0.71	5.95	----	83.6	499	----	----		----	
1:45		10.58	3.75	97.8	1037	4.63	538	4	144	1.8
4:00		14.85	2.25	106.3	1582	4.27	545	4	242	3.0
9:40	0.71	13.97	----	76.6	1073	----	----		----	
1:00		18.82	3.33	89.2	1683	4.85	610	4	183	2.3
4:40		22.49	3.67	103.1	2324	3.67	641	4	175	2.2
9:30	0.57	21.17	----	76.7	1626	----	----		----	
3:00		27.64	5.50	97.5	2699	6.47	1073	4	195	2.4
4:15		27.84	1.25	102.2	2850	0.20	151	4	121	1.5
10:30	0.80	3.68	----	79.7	294	----	----		----	
3:15		5.81	4.75	84.2	490	2.13	196	2.4	41	2.1
3:45		6.00	0.50	84.7	509	0.19	19	2.4	38	1.9
9:00	0.51	1.50	----	80.0	120	----	----		----	
12:30		3.09	3.50	83.3	257	1.59	137	2	39	2.0
8:25		6.50	7.92	90.8	589	3.41	332	2	42	2.1
11:00	0.82	1.09	----	79.7	87	----	----		----	
3:00		----	----	----	----	----	----		----	
5:30		5.53	6.5	85.8	475	4.44	388	2.3	60	3.0
9:45	0.62	1.21	----	79.7	97	----	----		----	
4:15		4.79	6.5	85.8	411	3.58	314	3	48	2.4
1:15	0.68	0.34	----	79.7	27	----	----		----	
5:40		3.26	4.42	83.9	273	2.92	246	3	56	2.8

(Continued)

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Vol. STRIP(1)	Total Nickel In STRIP(g)	Ni (g/1)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
11:40	0.89	0.81	----	79.7	65	----	----		----	
3:40		3.06	4.00	83.5	255	2.25	190	3	48	2.4
12:25	0.89	0.47	----	79.7	38	----	----		----	
3:00		2.21	2.58	82.1	181	1.74	143	3	56	2.8
4:50		3.66	1.83	83.8	307	1.45	126	3	69	3.0
10:00	0.58	0.74	----	79.7	59	----	----		----	
2:15		6.76	4.25	95.6	648	6.02	589	2	139	1.7
5:15		10.11	3.00	107.0	1085	3.35	437	2	146	1.8
2:05	0.70	2.15	----	79.7	172	----	----		----	
4:20		5.52	2.25	88.2	488	3.37	316	3	140	1.7
12:30	0.89	0.87	----	79.7	69	----	----		----	
5:45		8.50	5.25	99.6	847	7.63	778	2	148	1.9
9:25	0.86	1.98	----	79.7	158	----	----		----	
3:50		11.17	6.42	104.0	1163	9.19	1005	2	157	2.0
11:55	0.84	2.41	----	79.7	192	----	----		----	
4:50		10.76	4.92	98.3	1059	8.35	867	2	176	2.2
1:15	0.80	1.76	----	79.7	141	----	----		----	
5:15		8.87	4.00	94.8	842	7.11	701	3	175	2.2

(Continued)

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Total Vol. STRIP(1)	Nickel In STRIP(g)	Ni (g/l)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
1:35	0.98	1.90	----	87.3	166	----	----		----	
5:30		17.60	3.92	102.1	1799	15.70	1633	3	416	5.2
1:35	0.87	1.03	----	79.7	82	----	----		----	
4:40		9.00	3.08	91.4	823	7.97	741	3	240	3.0
9:40	0.64	2.38	----	75.9	181	----	----		----	
1:15		8.23	3.58	89.5	737	5.85	556	3	155	1.9
10:00	0.48	4.41	----	83.7	370	----	----		----	
4:00		14.70	6.00	106.4	1566	10.29	1196	4	199	2.5
9:55	0.88	2.88	----	83.7	241	----	----		----	
11:45		7.11	1.83	90.7	645	4.23	404	4	220	2.8
7:55	1.28	3.23	----	83.7	271	----	----		----	
4:45		17.64	8.83	117.1	2069	14.41	1798	4	204	2.6
1:30	0.94	2.35	----	79.7	188	----	----		----	
4:45		8.06	3.25	92.0	743	5.71	555	2.5	171	2.1
7:30	1.31	7.53	----	79.7	601	----	----		----	
12:45		12.64	5.25	99.6	1260	5.11	659	2.5	125	1.6
1:25	1.09	12.05	----	79.7	962	----	----		----	
4:45		17.14	3.33	92.3	1584	5.09	622	2.5	187	2.3

(Continued)

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Vol. STRIP(l)	Total Nickel In STRIP(g)	Ni (g/l)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
11:00	0.94	4.88	----	81.7	399	----	----		----	
4:10		11.58	5.17	101.3	1174	6.70	775	2.5	150	1.9
2:00	0.91	7.79	----	85.2	664	----	----		----	
5:00		12.60	3.00	96.6	1218	4.81	554	2.5	185	2.3
9:30	0.90	12.08	----	85.2	1030	----	----		----	
3:00		17.82	5.50	106.0	1891	5.74	861	2.5	157	2.0
1:30	0.83	17.05	----	85.2	1454	----	----		----	
8:00		23.78	6.50	109.8	2614	6.73	1160	2.4	178	2.2
1:15	1.18	23.00	----	78.7	1812	----	----		----	
5:40		27.87	4.42	95.4	2663	4.87	851	2.5	193	2.4
1:30	1.20	25.49	----	78.7	2009	----	----		----	
6:15		30.14	4.75	96.7	2918	4.65	909	2.5	191	2.4
2:15	0.86	5.32	----	81.7	435	----	----		----	
6:15		9.70	4.00	89.3	867	4.38	432	2	108	2.7
11:30	1.24	4.06	----	81.7	332	----	----		----	
6:25		11.47	6.92	94.8	1089	7.41	757	2	109	2.7
10:15	1.74	10.29	----	79.7	821	----	----		----	
4:30		15.88	6.25	91.5	1455	5.59	634	2	101	2.5
1:30	1.16	5.40	----	83.7	453	----	----		----	
5:30		11.00	4.00	98.8	1089	5.60	636	2.5	159	2.0

(Continued)

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Total Vol. STRIP(1)	Nickel In STRIP(g)	Ni (g/l)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
10:00	0.77	13.40	----	79.7	1069	----	----		----	
4:30		17.60	6.50	104.3	1838	4.20	769	2.5	118	1.5
8:00	0.92	6.8	----	79.7	543	----	----		----	
1:20		11.5	5.33	99.9	1150	4.7	607	2.5	114	1.4
1:30	1.09	10.2	----	79.7	814	----	----		----	
4:40		13.3	3.17	91.7	1221	3.1	407	2.5	128	1.6
8:30	0.73	15.2	----	79.7	1213	----	----		----	
3:40		21.5	7.17	106.8	2300	6.3	1087	2.5	152	1.9
11:30	0.88	0.23	----	61.8	14	----	----		----	
4:30		11.80	5.00	80.7	953	11.57	939	3	188	2.4
1:10	0.94	14.2	----	59.3	843	----	----		----	
7:25		21.8	6.25	83.0	1810	7.6	967	3	155	1.9
12:30	0.28	16.0	----	61.8	989	----	----		----	
3:30		18.6	3.00	73.2	1361	2.6	372	5	124	1.6
12:30	0.83	8.1	----	61.8	501	----	----		----	
6:45		19.0	6.25	85.5	1625	10.9	1124	3	180	2.2
11:25	0.75	10.0	----	61.8	618	----	----		----	
4:25		17.4	5.00	80.7	1405	7.4	787	3.5	158	2.0

(Continued)

TABLE 20

NICKEL TRANSPORT BY DONNAN DIALYSIS

TIME	FEED	STRIP	HR.	Corrected Total Vol. STRIP(1)	Nickel In STRIP(g)	Ni (g/l)	Ni (g)	Flow (gpm)	Nickel Transport (g/hr)	Flux ($g/hr/ft^2$)
12:25	0.73	24.4	----	78.2	1910	----	----		----	
4:10		27.2	3.75	99.5	2706	2.8	796	3	212	1.8
12:55	0.81	9.0	----	62.8	566	----	----		----	
5:05		17.0	4.17	86.5	1471	8.0	905	3	217	1.8
12:20	0.39	19.0	----	93.8	1783	----	----		----	
5:45		22.6	5.42	124.6	2815	3.6	1032	5	190	1.6
12:10	0.52	30.7	----	71.9	2208	----	----		----	
5:05		32.5	4.92	99.8	3245	1.8	1037	5	211	1.8
12:45	0.55	28.3	----	77.6	2196	----	----		----	
3:30		28.3	2.75	93.2	2638	0	442	3	161	1.3